Surface Brightness Profiles of Three New Dwarf Spheroidal Companions to M31

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ABSTRACT

CCD images of three newly discovered dwarf spheroidal companions to M31, And V, VI, and VII, are used to extract surface brightness profiles and total magnitudes. Using distance modulii provided by Armandroff et al. (1998 & 1999) and Grebel & Guhathakurta (1999), these galaxies are shown to have similar luminosities to other Local Group dwarf spheroidals; And V in particular is similar to Draco & UMi in luminosity, i.e., among the faintest known. In the luminosity-metallicity relation, And V is shown to have a significantly higher metallicity than expected.

Subject headings:

1. Introduction

In the last 20 years, 3 new dwarf spheroidal galaxies around the Milky Way have been discovered (dwarf spheroidals, dSph, are defined here to be the faintest of the dwarf ellipticals, fainter than $M_V = -14$). These are Carina (Cannon et al. 1977), Sextans (Irwin et al. 1990) and Sagittarius (Ibata et al. 1994). An additional dSph, Tucana, was found unassociated with a large galaxy, but still located within the boundaries of the Local Group (Lavery & Mighell 1992). Around M31, there had been no searches and no discoveries of new dSph's since the work of van den Bergh (1972) who found the And I, II and III galaxies (And IV proved not be be a dSph, though its nature is still to be settled). This past year has seen the efforts of two groups scanning the sky around M31, and resulting in the discovery of 3 new M31 companions (Armandroff et al. 1998, Armandroff et al. 1999, Karachentsev & Karachentseva 1999). All three of these dwarfs have now been the subject of detailed study of the resolved stellar populations, resulting in distance and metal abundance estimates (Armandroff et al. 1998, Armandroff et al. 1999, Hopp et al. 1999, Grebel & Guhathakurta 1999). HST observations are planned for two of these as well, which will provide higher precision values for those parameters, as well as age, and metal abundance spread estimates. The basic parameter of apparent magnitude, and thus luminosity, for all three of these galaxies are as yet unmeasured with adequate accuracy, though the luminosities are needed in discussions of the luminosity-metallicity relations, for instance (Caldwell et al. 1998). Measuring the total magnitudes of dSph's is difficult for nearby systems that subtend a large angle, thereby requiring the technique of counting resolved stars down to a certain magnitude: witness the large errors in luminosities (typically 0.5 mag) reported for UMi by Caldwell et al. (1992) and Irwin & Hatzidimitriou (1995). Surface photometry is possible for systems of smaller angular size (either smaller physically or simply more distant such as the M31 companions), and though the work requires a bit of care, it is straightforward and can result in luminosity uncertainties as small as 0.1 to 0.2 mags (Caldwell et al 1992). Thus this paper is concerned with the task of providing measured luminosities from surface photometry for the new M31 companions And V, VI and VII. The work is laid out as follows. Observations and reductions are described in the next section, followed by the presentation of the light profiles and luminosities, using distances from other sources. A few comments are made at the end regarding how these three galaxies fit into the relations among surface brightness, luminosity and metallicity.

And VI is also called Peg dSph and And VII is called Cas dSph by Grebel & Guhathakurta (1999). I choose to follow the orginal naming convention of van den Bergh, who named the companions for the galaxy host, and not the constellations in which they were discovered (e.g., And II is in fact in Pisces), particularly since it has already been shown that these objects are in fact all at the distance of M31.

2. Observational Data

The three new M31 companions were observed with the FLWO 1.2m telescope on Mt. Hopkins on the photometric night of 1998 Dec 11, using the “4shooter” CCD camera, a mosaic of 4 2048×2048 Loral CCD's. Four 600s exposures in the V band were taken of And V and VI, while three such exposures were taken of And VII. The telescope was moved by approximately 20″ between each exposure. A dark night sky flatfield was constructed from other data taken that night and used to flatten the dwarf frames, after debiasing. Individual frames were shifted to a common center, and were then combined using a simple sum, since the few cosmic rays detected would be removed in the isophote fitting process. The CCD's were binned on the chip 2×2, which resulted in pixel sizes of 0.67″, giving a field of 11.4′ per CCD frame. Because of the difficulty in getting different chips of a mosaic to have the same photometric scale to better than 1%, only the frame that contains the galaxy in question was used in the analysis. After summing, each pixel contained around 20,000 e^- (except for the And VII data which of course had 75% of that value) due to the sky. This value is comparable to the sky level obtained for the And I-III data in Caldwell et al. (1992), when account is taken of the different pixel scales, thus I should expect to obtain the same quality of data. The dark-sky flattened frames are flat to 4×10^{-4} peak-to-valley in radial bins, which is about as good for the And I-III data. Fig. 4 shows a montage of the 1.2m CCD frames on these three galaxies.

The And I-III Schmidt CCD frames of Caldwell et al. (1992) were much larger on the sky than the 1.2m data here (40′ vs 11′), prompting some concern that the present data may not cover sufficient area to allow the full areal extent of these new dwarfs to be realized. For instance, And I and II reach a surface brightness of 31 mag arcsec^{-2} at about 500″, which would be the limit in radius of the 1.2m frames. This is certainly not a problem for the small And V galaxy, but may affect And VI and VII in that the derived light profiles may be a bit steeper than they should. The total magnitudes of these two should not be seriously affected however, as even for And I, only 0.15 mag of the total is found outside of 300″. I will add 0.1 mag in quadrature to the uncertainties in the derived total magnitudes for And VI and VII to account for this concern.

The largest source of uncertainty in the new data frames is caused by the presence of bright stars in the fields. These are masked off first automatically, by detecting all pixels above a predetermined threshold and masking them (the level is set so that resolved stars that are members of the dwarfs are below the level), and then by hand masking halos of bright stars and stars within the confines of the dwarfs that are clearly foreground. The center of And V is somewhat contaminated by foreground stars and thus the light profile of its central area is more uncertain than the others. Contrawise, the outer areas of And VII are contaminated by very bright stars, hence its profile does not extend as far as the others.

Uncertainties in the mean sky level of course dominate the photometric errors, and were estimated along with the mean sky itself by collecting data in radial bins out from the dwarf centers to the edges of the frames. The sky level is then the mean value acheived at large radii, and the uncertainty is the scatter around that value. The scatter in the data for And VII was higher than that for the other two, because of the bright stars mentioned, and this is reflected in the quoted uncertainty for the derived photometric values.

An ellipse fitting program was used to collect the isophotes (Caldwell et al. 1992), once centering was set by eye. The axis ratios of And V and VII appeared to be circular and were fixed to those values for the isophote collection. The axis ratio for And VI was fit by the program, and a mean value for that and the position angle was determined and quoted here. Pixels with values more than 4σ above the mean isophotes were deleted, under the assumption that they were either cosmic rays or non-member stars. This deletion resulted in decreasing the total magnitudes by about 0.02 magnitudes for the dwarfs.

Photometric standards in 4 of Landolt's (1983) fields were observed during the night, over a range of airmasses. 24 stars were used to derive the transformation equation to V magnitudes; with a B–V color term a standard deviation of 0.02 mag was achieved. I thus have to assume a color (taken to be B–V=0.70) for the dwarf transformations (the color term coefficient is only 0.06, so a large amount of leeway in the actual color is allowed).

3. Light Profiles and Luminosities

Fig. 2 shows the derived radial light profiles for these three galaxies. Errors are indicated by the dotted lines above and below the surface brightness points, and are derived from photon statistics, readout noise and the uncertainty in the mean sky level. The profile for And VI matches well that done for the galaxy by Hopp et al. (1998). The differences are of the order of 0.05 mag in surface brightness, and there appears to be no systematic offset.

And V as expected is much smaller than the other two, and of lower surface central brightness. The central surface brightness for And VII is relatively high, is higher than any of And I-III, and indeed is next to Leo I and Fornax in this regard. Its brightness makes its delayed discovery more difficult to understand, aside from the obvious fact that no one looked in detail on sky survey plates in its area until the discovery group did (Karachentsev & Karachentseva 1999).

A number of important quantities can be derived from these light profiles; these are listed in Table 1. Radii are geometric means of the semi-axes, which only matters for And VI since the other two are taken to be circular in projection. The total apparent magnitude is calculated by summing up the profiles, to the point in radius where the isophote level goes to zero. The quoted uncertainties include the 0.1 mag value discussed in section 2 for And VI and VII. Absolute magnitudes are calculated using the distance modulii from Armandroff et al. (1998, 1999) and Grebel & Guhathakurta (1999). Errors are the quadratic mean of those of the apparent magnitudes and the distance modulii. Reddenings listed are from Burstein & Heiles (1982) or Schlegel et al. (1998) for And V and VI (used by Armandroff et al. 1998 and 1999 in determining metallicities via the color of the giant branches), and from Grebel & Guhathakurta (1999) for And VII, a combination of reddenings from Burstein & Heiles and Schlegel et al. The Schlegel et al. new Galactic reddening description gives a somewhat smaller reddening than Burstein & Heiles for And V, and a somewhat larger reddening for And VI.

And V has an unusually faint total magnitude, of $M_V = -9.1$, which puts it in the realm of the faintest Galactic dSph's, Draco, Uminor, and Carina (and in fact And V now has the most accurate measure of M_V for any of these). Hopp et al. (1999) had quoted an $M_V = -10.4$ for And VI, but this value is in fact only the magnitude within a V surface brightness of 25.5 mag arcsec^{-2} as stated in their text, and not the total magnitude which as shown here is nearly 1 magnitude brighter, at $M_V = -11.3$. The $M_V = -12.0$ for And VII places it next in luminosity just below Fornax and Sagittarius in the Local Group.

Central surface brightnesses are estimated directly from the light profiles; the values in Table 1 are corrected for the quoted extinctions. As mentioned, the foreground stars near the center of And V make its central surface brightness more uncertain than is the case for the other two. The value here of $V_0 = 24.8$ is higher than found in Armandroff et al. (1998) by 0.4 mag. This appears to be due to the fact that those authors averaged the data over the central 20″. Averaging the present And V data over that region results in a similar value to that of Armandroff et al. The value for And VI of $V_0 = 24.36 \pm 0.05$ matches well that of 24.2 shown in Fig 2 of Hopp et al. (1999). (This is not the value quoted in their text, which refers to their exponential fit.)

Sersic profiles ($I=I_0 e^{-(r/r_0)^n}$, Sersic 1968), which have an additional free parameter n over an exponential (n=1), were fit to the data. Table 1 shows the derived values ($S_0 = -2.5\log_{10} I_0$ and is corrected for extinction). As is typical for the faintest dSph's, And V has a profile much steeper than an exponential.

The empirical core radii refer to the radius at which the local surface brightness has fallen to half the central value. These were measured directly off of the profiles. Effective radii refer to the radius which contains half the total light, and were likewise obtained directly from the profiles. And VI and VII are typical sized dSph's for the Local Group. And V is among the smallest, its $R_e = 145$ pc being smaller than UMi (190, Caldwell et al. 1992) and Carina (190), and close to that of Draco (133, Irwin & Hatzidimitriou 1995 for the last two). Again, the value for And V is more accurate than those for the Galactic dwarfs.

4. Comments

How do these three new M31 dwarfs fit it with the family of dwarf ellipticals? Fig. 3 shows the relation between luminosity and central surface brightness, a diagram discussed in Caldwell et al. (1998). The new M31 dwarfs occupy the same area as the other Local Group dwarfs occupy. And V as noted above is among the faintest known dSph's. And VII appears to have high surface brightness for its luminosity, though not nearly as strong a case as Leo I. As a group, the 6 known M31 companions are very similar to the 8 known Galactic dSph's.

The detailed work on the resolved stellar populations of And V and VI by Armandroff et al. (1998 and 1999), and on And VI and VII by Grebel & Guhathakurta (1999) have provided good estimates of the mean metallicities of these dwarfs from the colors of the giant branches, and thus allow a further comparison of these dwarfs with others to be made. The relation between luminosity and metallicity for old stellar populations is now well studied, if not yet completely understood (Mould, Kristian, and Da Costa 1983, Caldwell et al. 1998, Mateo 1998). There appears to be a similar relation for star forming dwarfs (Aaronson 1986, Skillman et al. 1989, Richer & McCall 1995); comparing the two requires knowing [O/Fe] in most cases because the kinds of metallicities measured for the two types of dwarfs are different ([Fe/H] of stars for dSph's; [O/H] for star forming dwarfs). Fig. 4 shows the new M31 dwarfs in relation to other dwarfs whose metallicities have been measured in the same way, in the luminosity-metallicity plane, and in the surface brightness-metallicity plane. For And V and VI, the [Fe/H] values (–1.5 & –1.58, respectively) of Armandroff et al. (1998 & 1999) have been chosen, while for And VII the [Fe/H]= –1.4 comes from Grebel & Guhathakurta (1999).

And VI and VII appear to have [Fe/H] values expected for their luminosities, but And V has a metallicity high for its very low luminosity. If the lower Schlegel et al. (1998) reddening is adopted for And V, it's metallicity of course increases, making the discrepancy even larger (the other faint dSph's are not much affected by changes in adopted reddening). The range in [Fe/H] for galaxies with $M_V \sim -9$ is about 0.7. This is not as large as the range in [Fe/H] for galaxies with low surface brightness (1.2), so it still seems clear that luminosity is the dictating factor in a dwarf's mean metallicity. Clearly, a larger sample of the new, very faint dSph, either in the Local

Group or in nearby groups, which also would be studied in detail, would be helpful in this matter.

Mateo (1998) interprets the luminosity-metallicity relation as being bi-modal, based on the fact that the Local Group dSph galaxies brighter than $M_V \sim -14$ had lower metallicities than an extrapolation of the relation determined by all fainter galaxies would predict. New metallicities for those brighter galaxies from Han et al. (1997) and Geisler et al. (1999) are shown in Fig 4, indicating that the relation defined by the lower galaxies extends well into the brighter galaxy region, thus negating the need for a bimodal interpretation. The position of And V in this relation, with its metallicity offset of $\sim +0.5$ dex from the other galaxies in its luminosity bin, however, shows that a large scatter exists for the lower luminosity galaxies. It may be that the scatter at all luminosities in the relation is larger than currently evident - more data on luminous galaxies would be helpful.

Finally, And V's high metallicity for its luminosity may imply an even deeper potential well than is the case for say, Draco and Umi (Pryor & Kormendy 1990). If so, its stellar velocity dispersion would thus be higher than those two, and so also its M/L ratio. Securing stellar kinematics of this galaxy then takes on an even larger importance, for the the similarity of dark matter halo densities for low mass halos could be investigated (Navarro et al. 1997).

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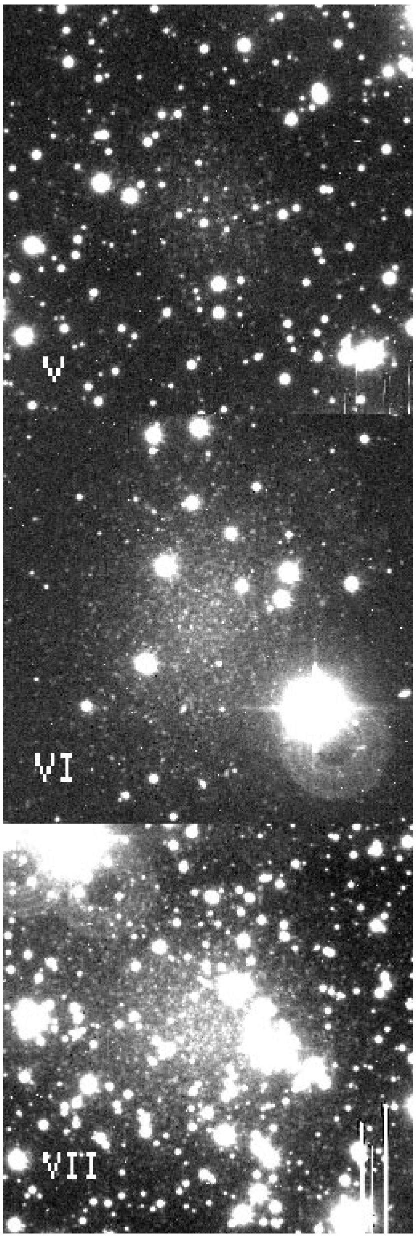


Fig. 1.— 1.2m images in V of the three M31 companions And V, VI and VII. North is up; east to the left. Field diameter for each image is 5.7′ (about half of the total diameter of the images) The intensity scale for all three images is the same.

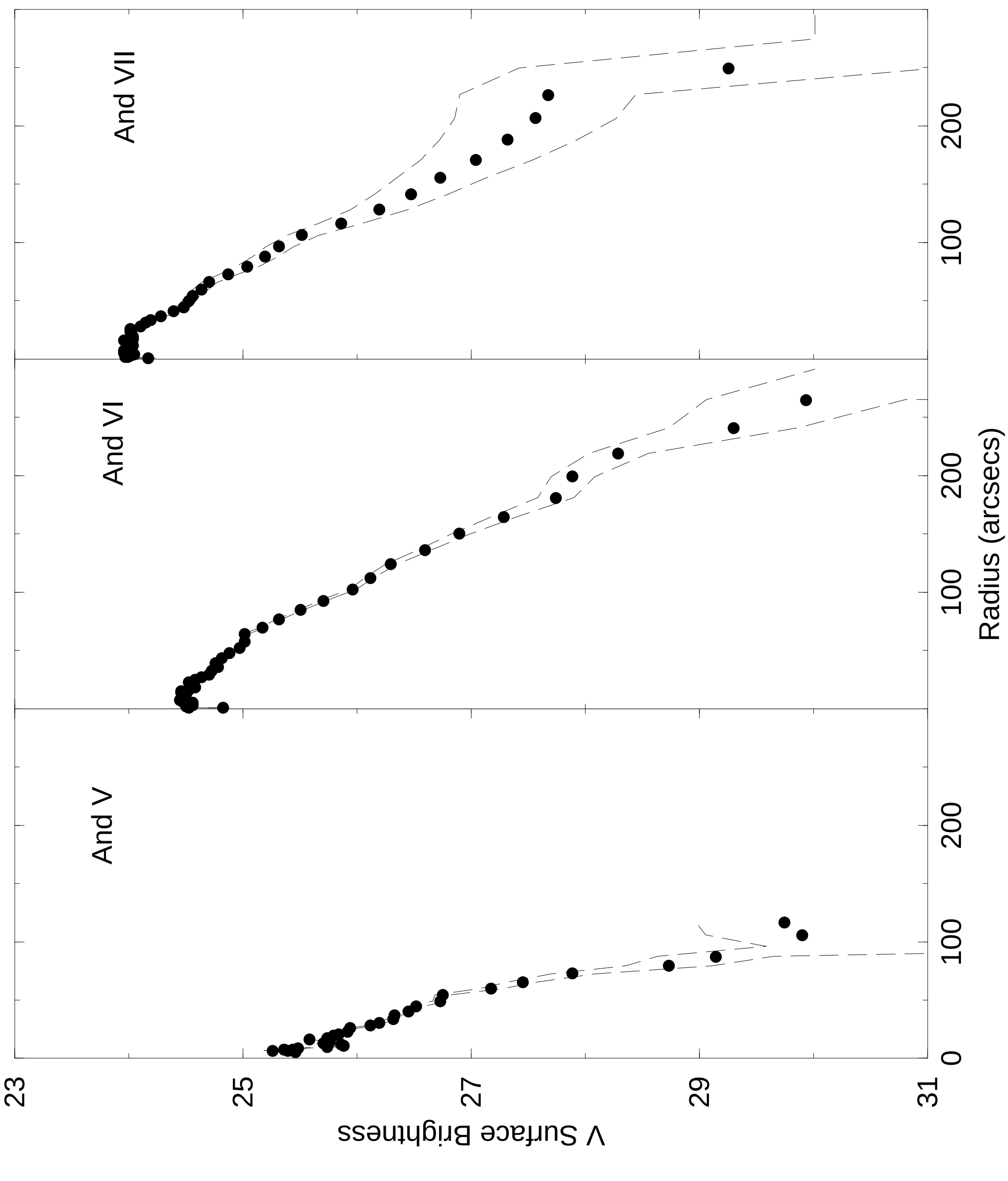


Fig. 2.— Radial light profiles of the three M31 dwarfs. Surface brightness in V mags arcsec^{-2} is plotted against the geometric mean of the semi-axes in arcsecs. Dashed lines show 1σ error bars in the surface brightnesses.

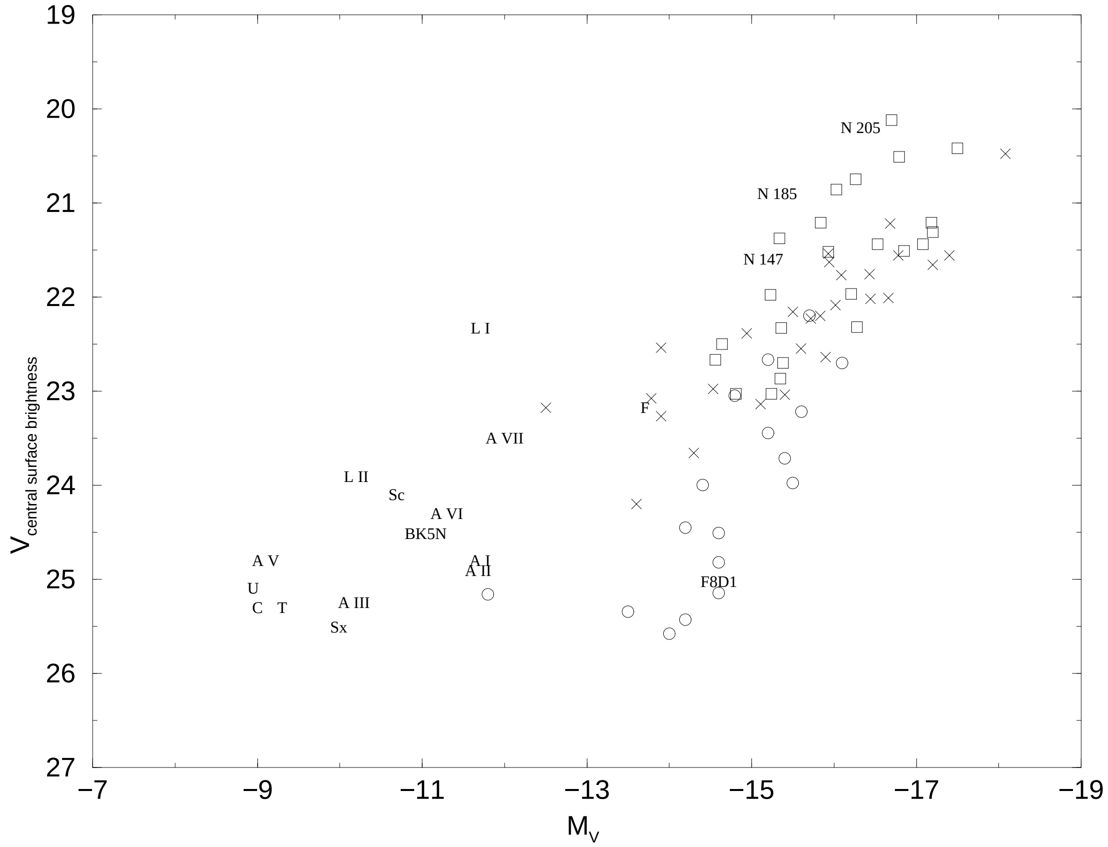


Fig. 3.— Relation between central surface brightness and M_V for dwarf ellipticals. Crosses and open squares represent Virgo and Fornax dE's; circles represent the large, low surface brightness galaxies found in Virgo by Impey et al. (1988); Local Group dE's are shown with abbreviations for their names; and the M81 group dwarfs, BK5N and F8D1, are shown with their names. Draco is not plotted because neither its central surface brightness nor its luminosity are as well known as the other galaxies plotted here.

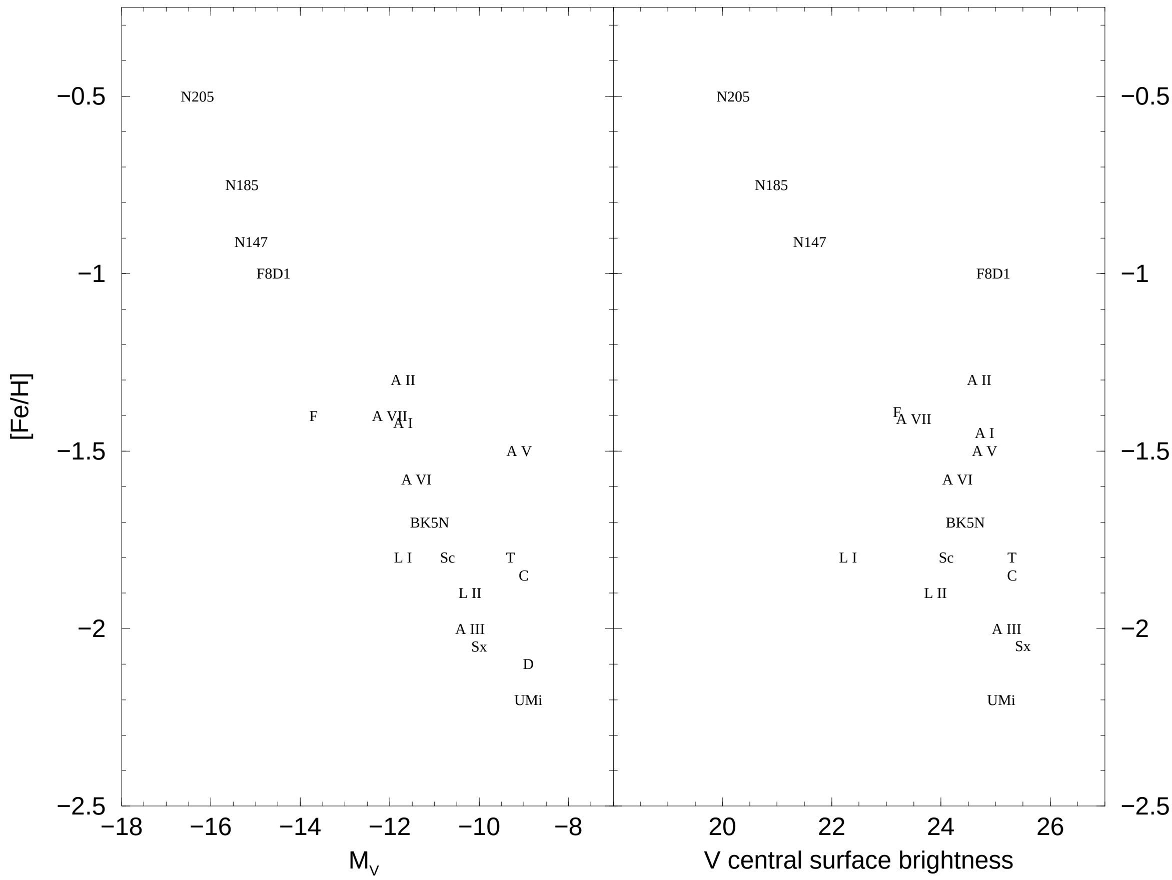
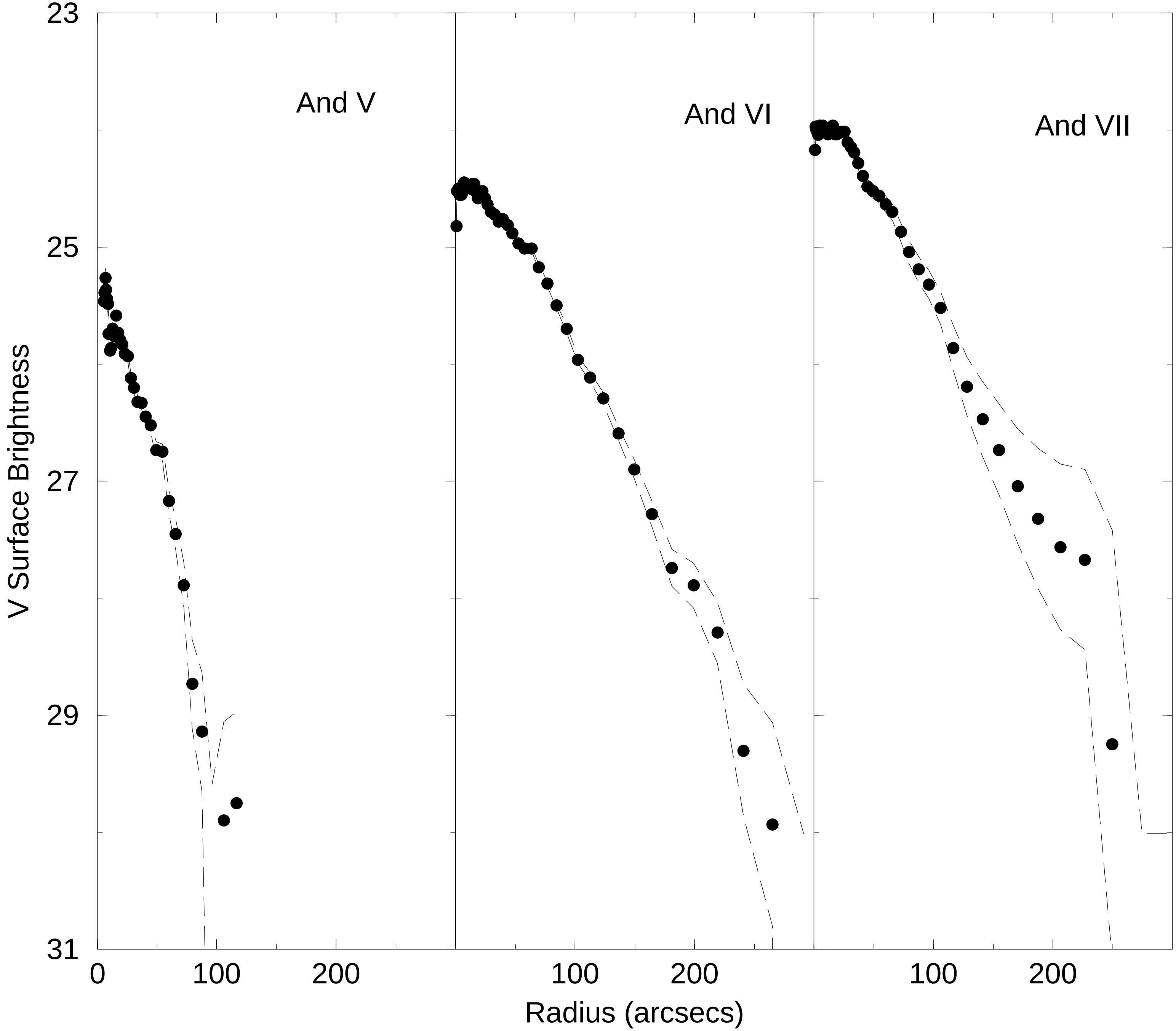


Fig. 4.— Relation between metallicity ([Fe/H]) and M_V; and metallicity and central surface brightness. Additional new metallicities shown in this plot (changes over what was shown in Caldwell et al. 1998) are those of NGC 147 (Han et al. 1997) and NGC 185 and 205 (Geisler et al. 1999).

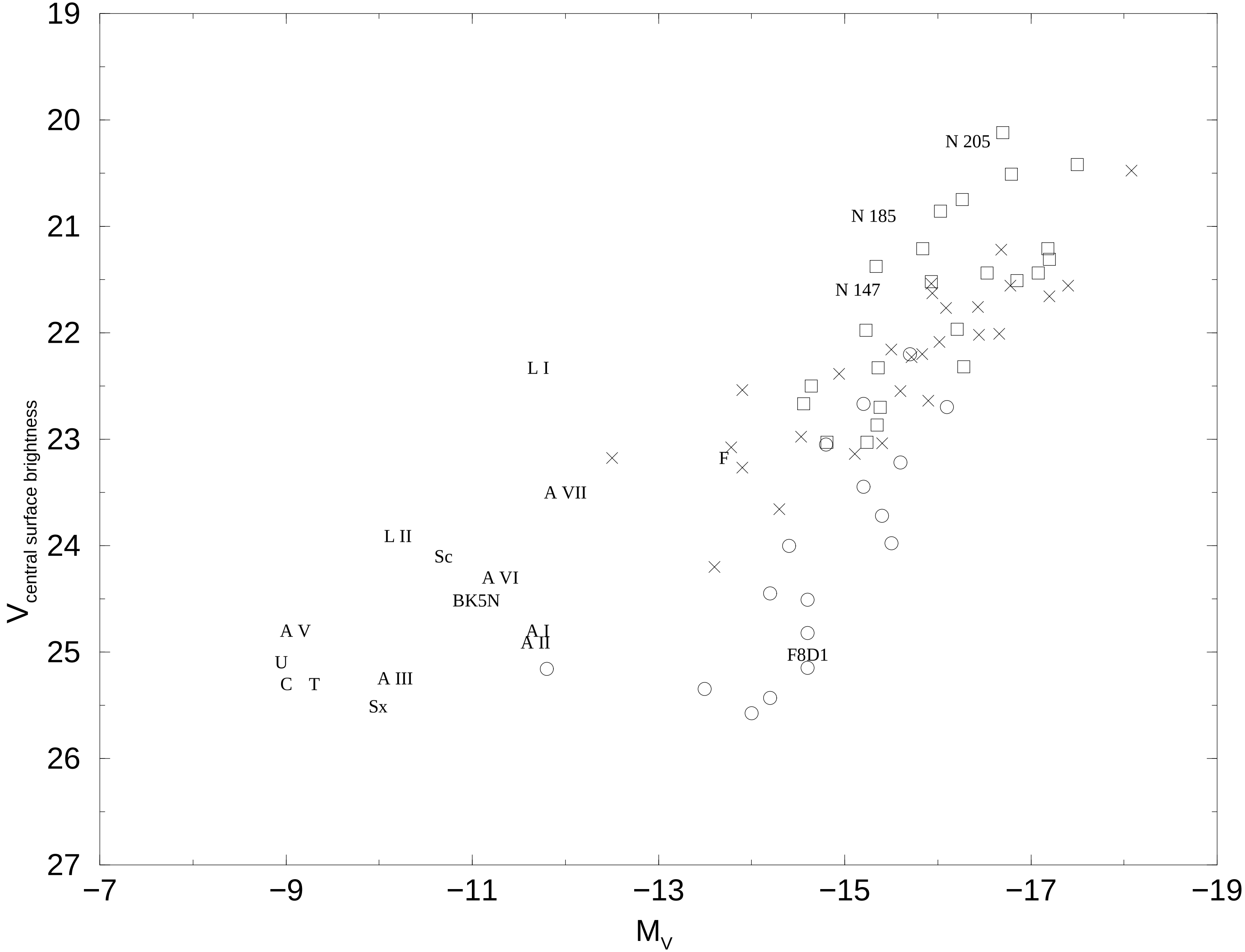
Table 1. Basic Data for And V, VI, and VII

Parameter	And V	And VI	And VII
RA_{J2000}	01:10:17.1	23:51:46.3	23:26:31
Dec_{J2000}	47:37:41	24:34:57	50:41:31
$(m–M)_0$	24.55 ± 0.12	24.45 ± 0.1	24.4 ± 0.2
V_{tot}	15.92 ± 0.14	13.30 ± 0.12	12.90 ± 0.27
M_V	-9.1 ± 0.2	-11.3 ± 0.2	-12.0 ± 0.3
V_0	24.8 ± 0.20	24.31 ± 0.05	23.47 ± 0.05
r_c(pc)	110	286	240
R_e(arcsec)	37	84	80
R_e(pc)	145	316	295
S_0	25.01 ± 0.06	24.20 ± 0.03	23.34 ± 0.03
r_0(arcsec)	45 ± 2	82 ± 2	75 ± 2
n	1.7 ± 0.16	1.38 ± 0.04	1.32 ± 0.04
1-b/a	0	0.23	0
PA	···	160	···
A_V	0.50	0.19	0.53

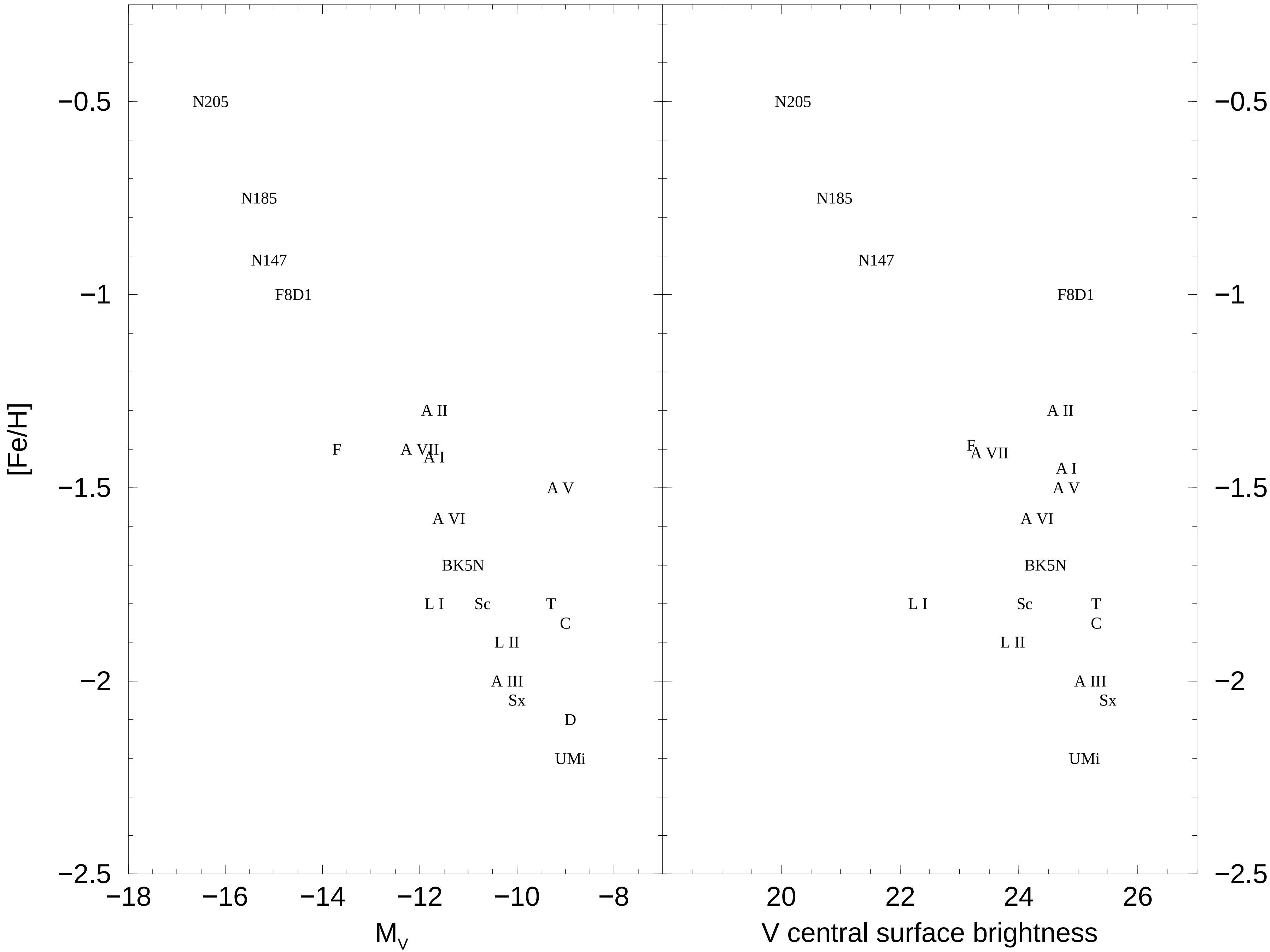
Coordinates and distance modulus for And V and And VI from Armandroff et al. (1998, 1999); those for And VII from Grebel & Guhathakurta (1999). Surface brightness values are dereddened.



And V
And VI
And VII
V Surface Brightness
23
25
27
29
31
0
100
200
100
200
100
200
Radius (arcsecs)



N 205
N 185
N 147
L I
F
A VII
L II
Sc
A VI
BK5N
A V
A I
A II
F8D1
U
C
T
A III
Sx
$V_{\text{central surface brightness}}$
M_V



[Fe/H]
M$_V$
V central surface brightness
N205
N185
N147
F8D1
A II
F
A VII
A I
A V
A VI
BK5N
L I
Sc
T
C
L II
A III
Sx
D
UMi